Stratospheric Impacts of the Hunga Tonga-Hunga Ha'apai Eruption Water Vapor Injection

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Background & Motivation

The January 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption injected a substantial amount of water vapor directly into the mid-stratosphere.

MLS observations suggest ~150 Tg of water vapor was added to the stratosphere, a ~10% increase.

This enhanced water vapor significantly altered the radiative balance, dynamics, and photochemistry of the stratosphere.

Given the long lifetime of stratospheric water vapor, this perturbation is expected to have an impact for several years.

In this study we use a two-dimensional (2D) chemistry-climate model to simulate the stratospheric temperature and ozone responses in the months and years following the eruption

H_2O anomaly simulation

Use the GSFC 2D chemistry-climate model, used in WMO ozone assessment activities, including *WMO-2018, WMO-2022*

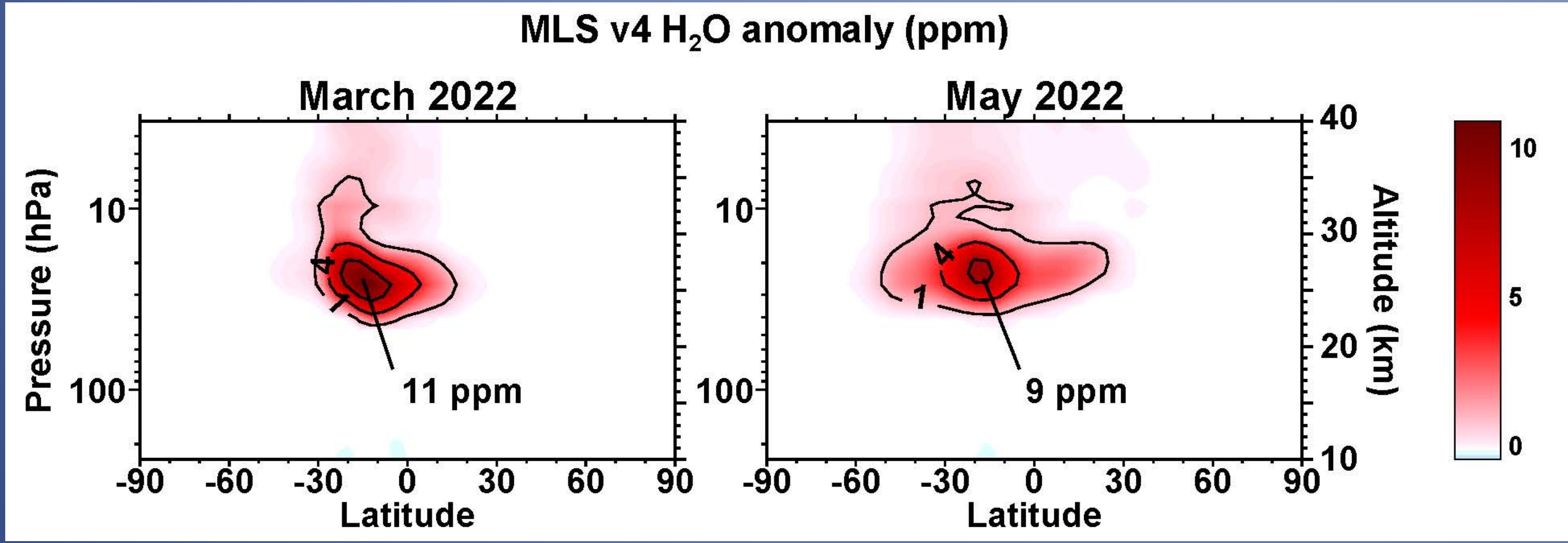
Compare model simulations with vs. without H_2O anomaly; include interactive QBO

Water vapor anomaly in latitude-height :

Use daily zonal mean MLS v4 data (Millán et al., 2022, GRL)
→ anomaly = difference from the 2005-2021 average for a given month

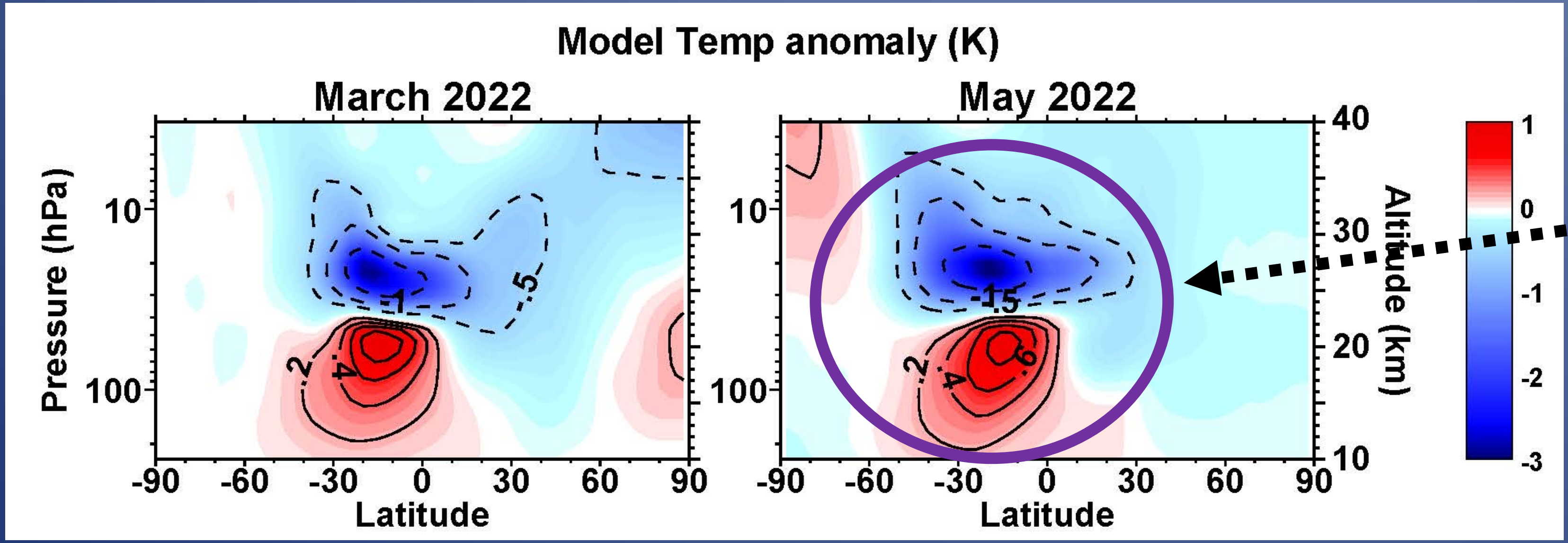
MLS water vapor anomaly is input into model for 16 January – 30 September 2022 then computed in model for 1 October 2022 through 2030

Water vapor and temperature response



Water vapor anomaly spreads in latitude and altitude

Concentrations diminish with time as plume disperses



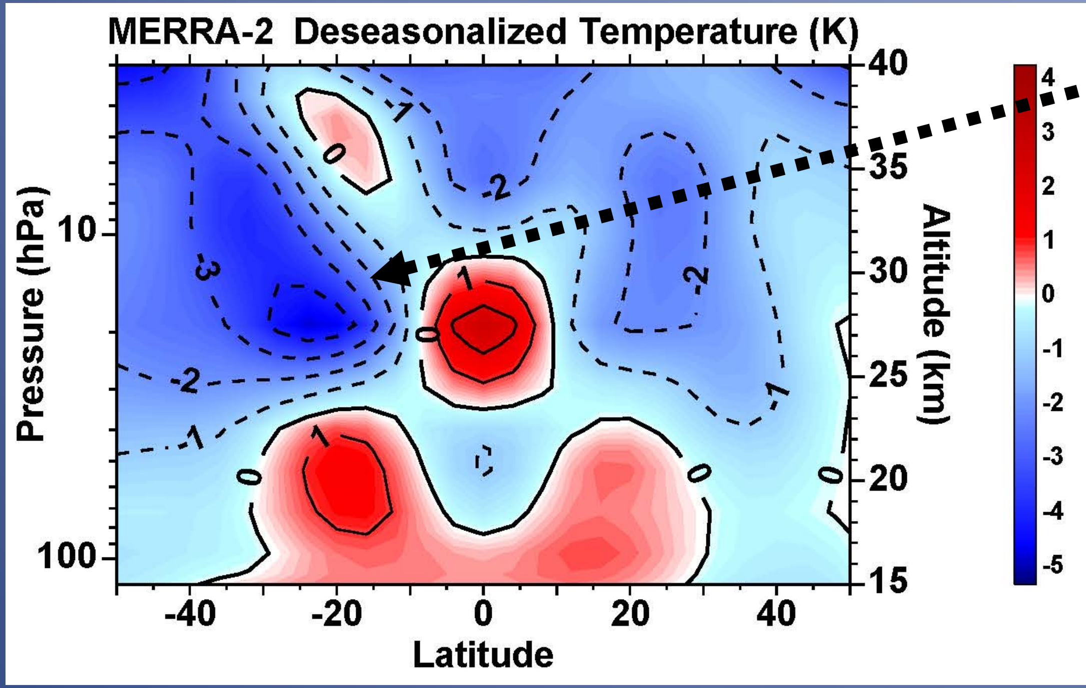
H_2O is a greenhouse gas

Max cooling of 2-3 K in mid-strat

Max warming of 1K in lower strat

Response diminishes with time

May 2022 temperature response



Very cold temperatures in SH mid-strat
in MERRA-2 data (-4K → -5K)
3-4 sigma colder than average

(see also Schoeberl et al., 2022, GRL
Coy et al., 2022, GRL)

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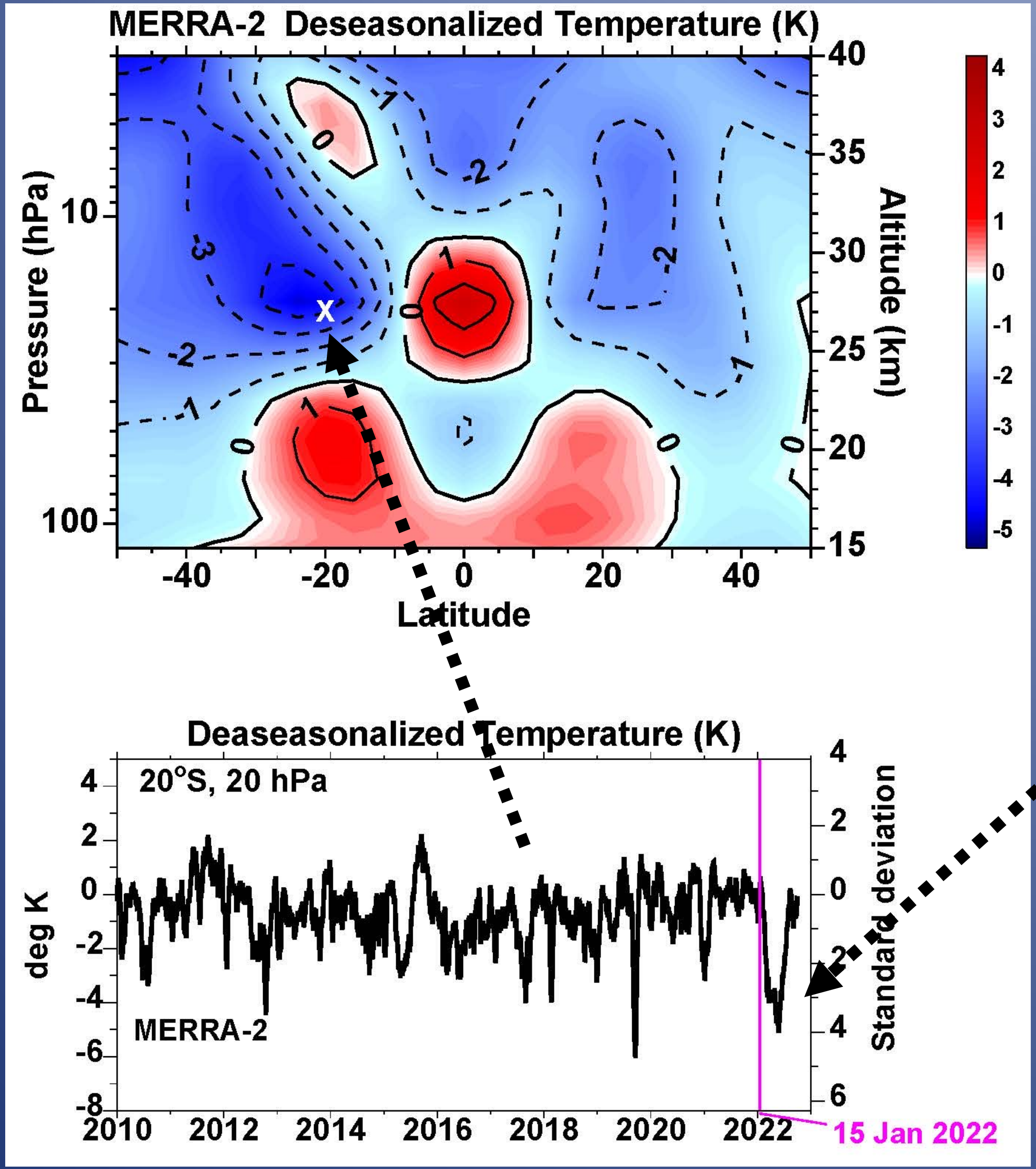

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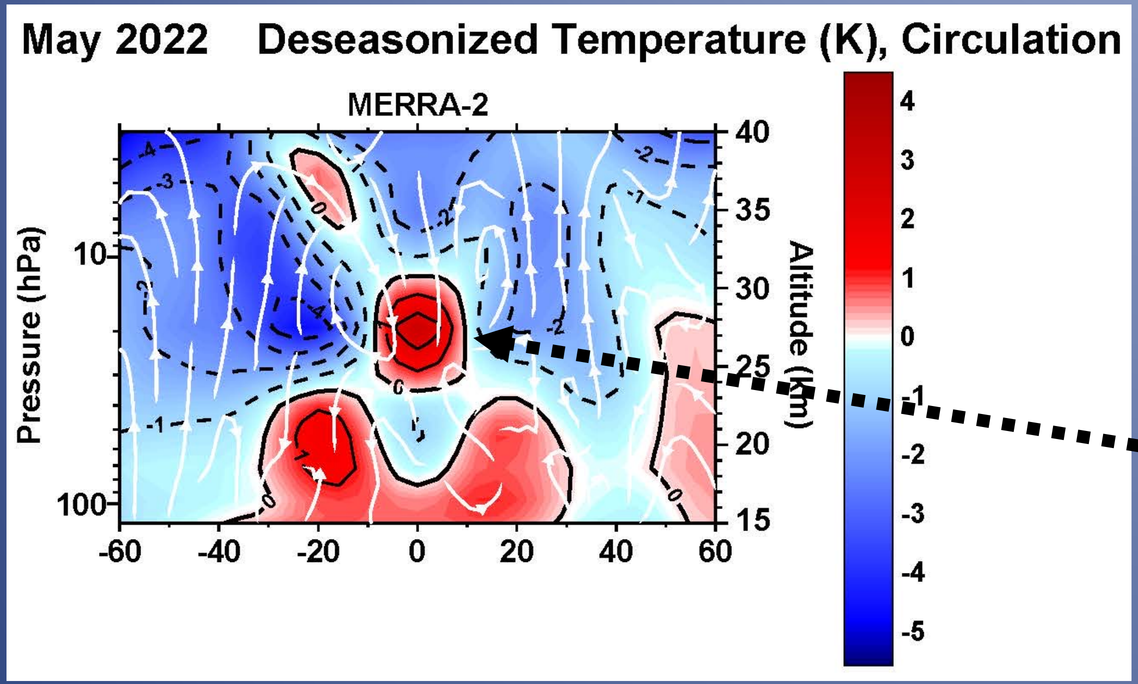
-5K at 20°S, 20 hPa in May 2022
4σ colder than average

2nd coldest time period during 1980-2022
MERRA-2 record

May 2022 temperature response



QBO Phase: Easterlies in equatorial stratosphere below ~20 hPa in May 2022

Important for meridional circulation associated with the QBO (Plumb and Bell, 1982)

Mid-stratosphere (10-40 hPa):

→ warm anomaly over equator (descent)

→ cold anomaly in SH subtropics (ascent)

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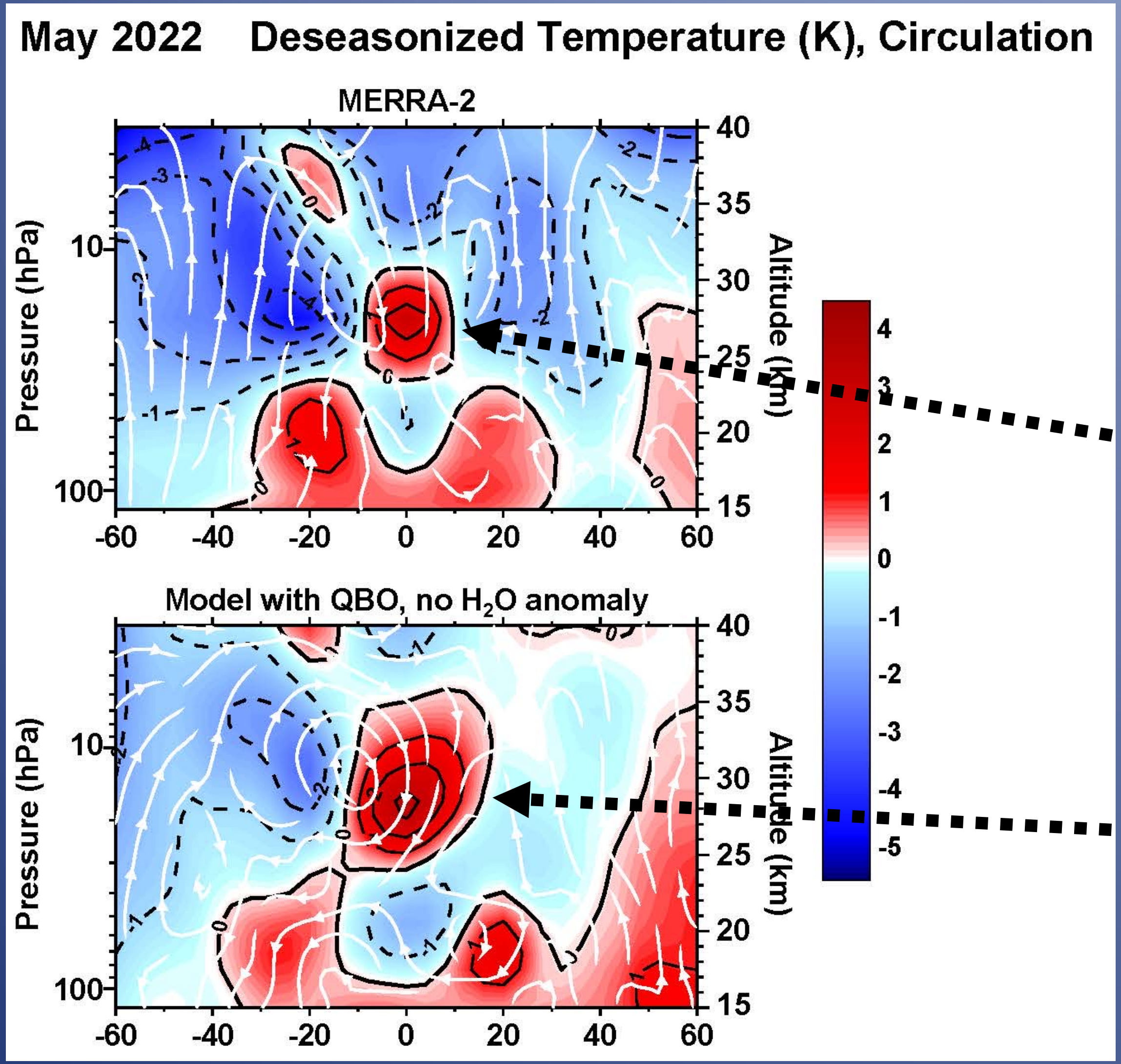

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- → warm anomaly over equator (descent)
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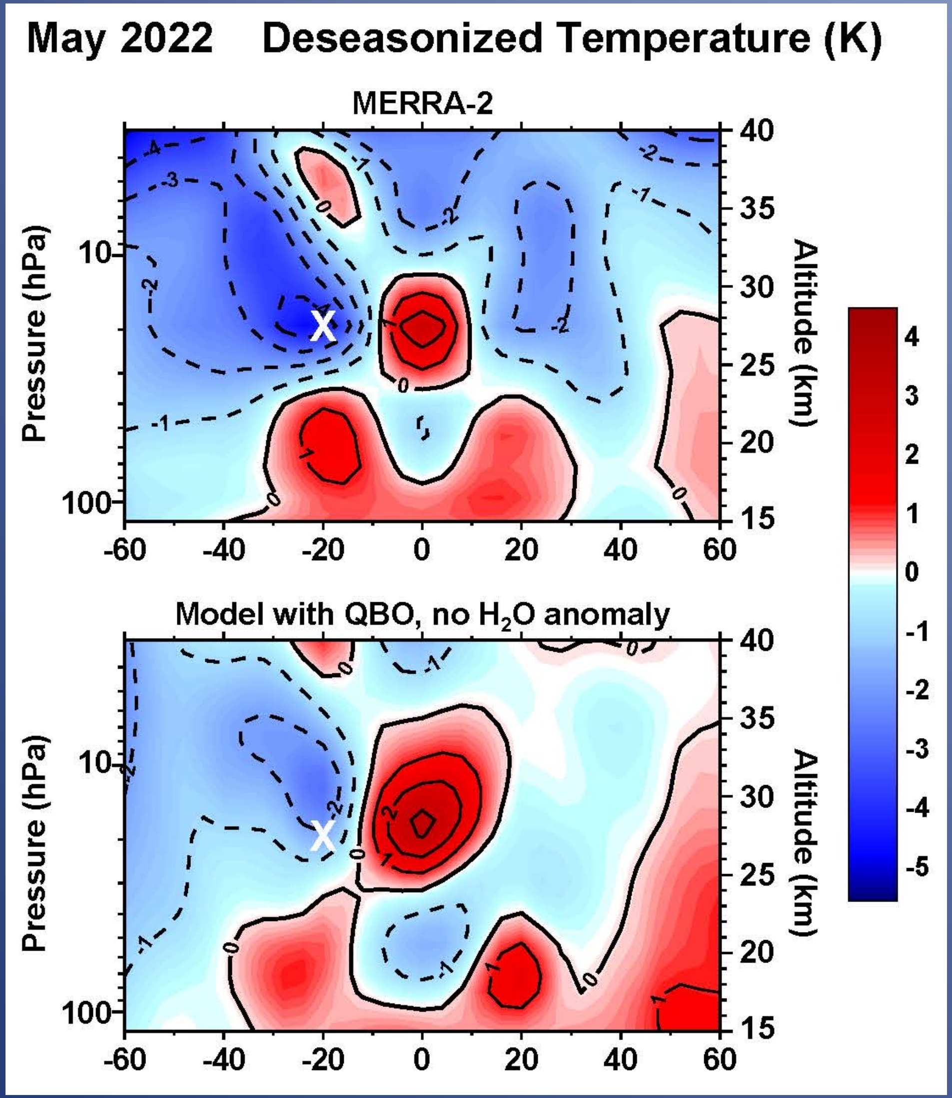
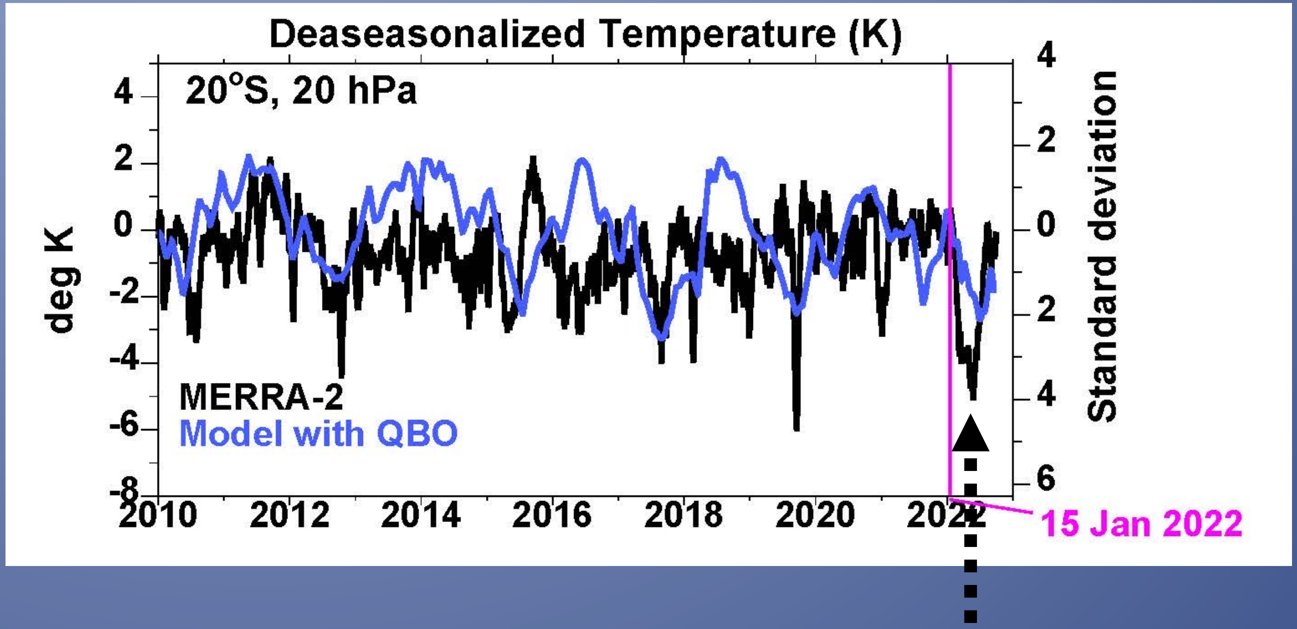
Model with interactive QBO in same phase (no H_2O anomaly) is generally consistent with MERRA-2 (model has weaker anomaly in SH)

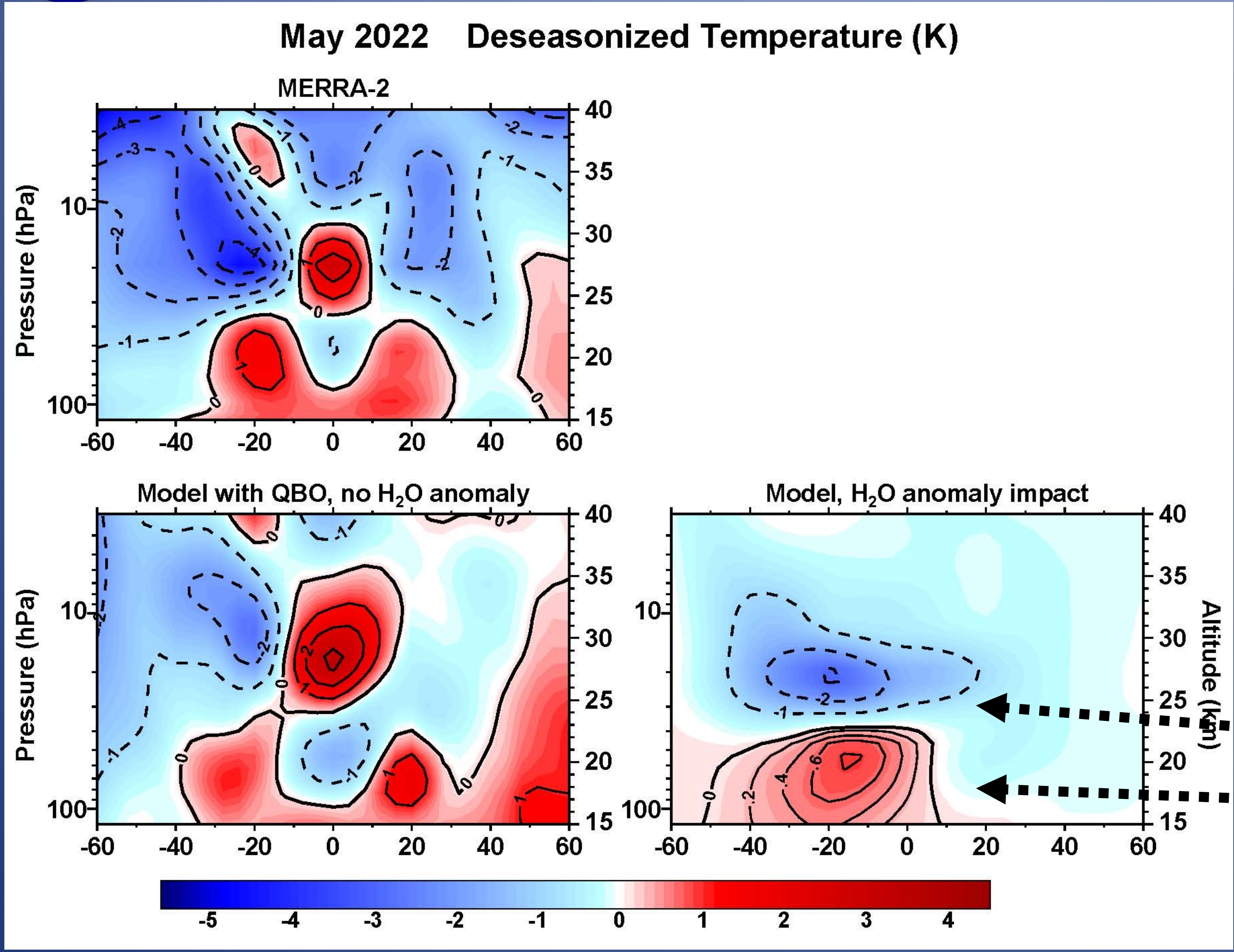
May 2022 temperature response





Model with QBO (blue) captures 30-40% of cold anomaly in May 2022

May 2022 temperature response

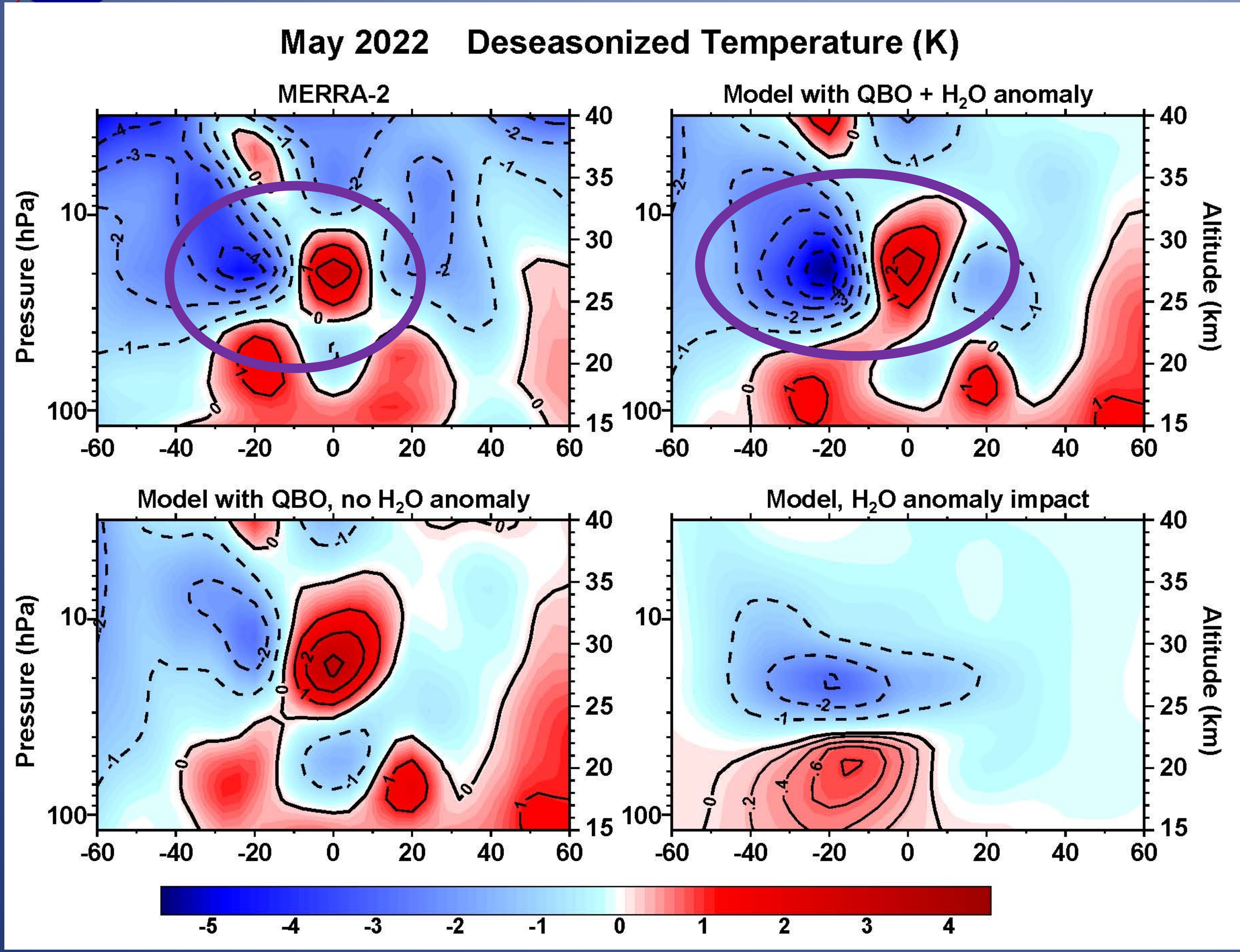


H_2O anomaly:

2-3K cooling in SH mid-strat

.6 - 1K warming in SH lower strat

May 2022 temperature response



Model with both QBO and H_2O anomaly gives temperature anomalies consistent with MERRA-2

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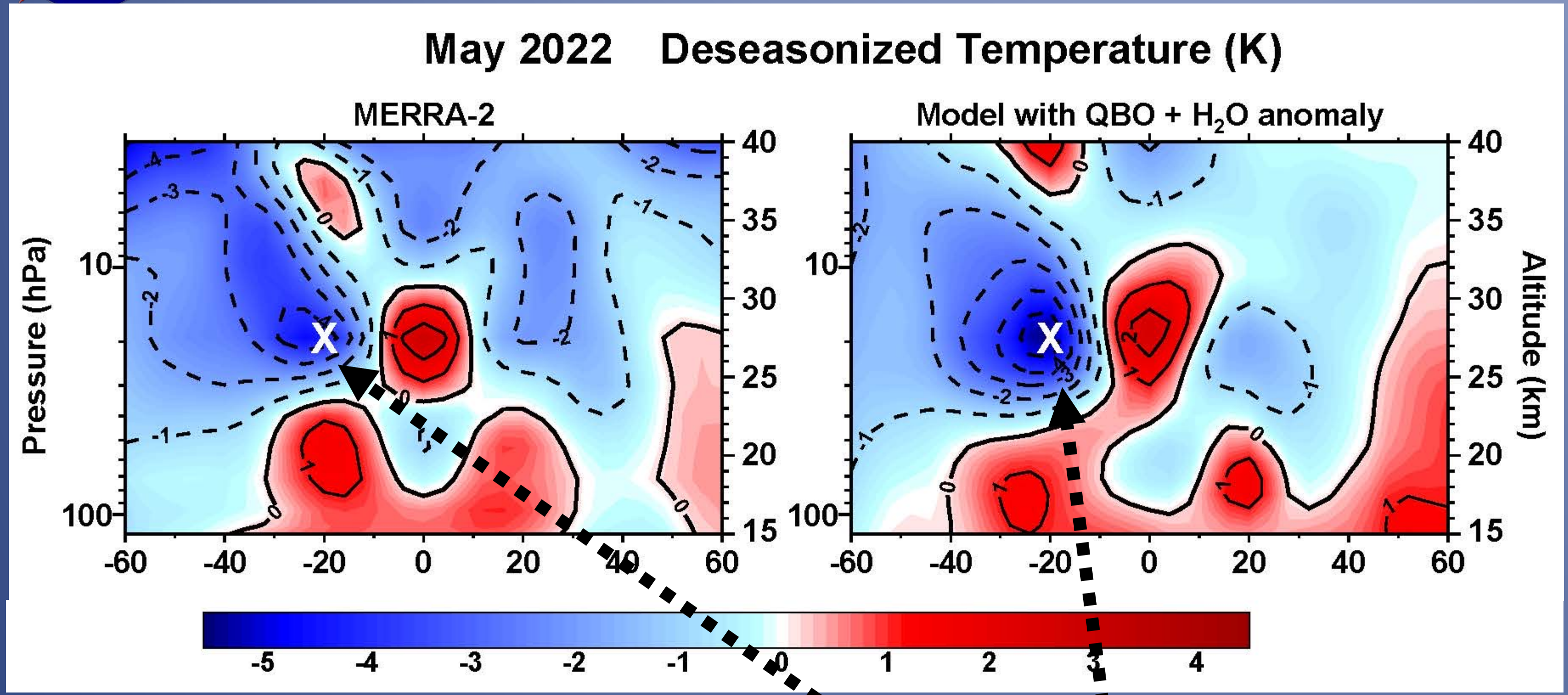

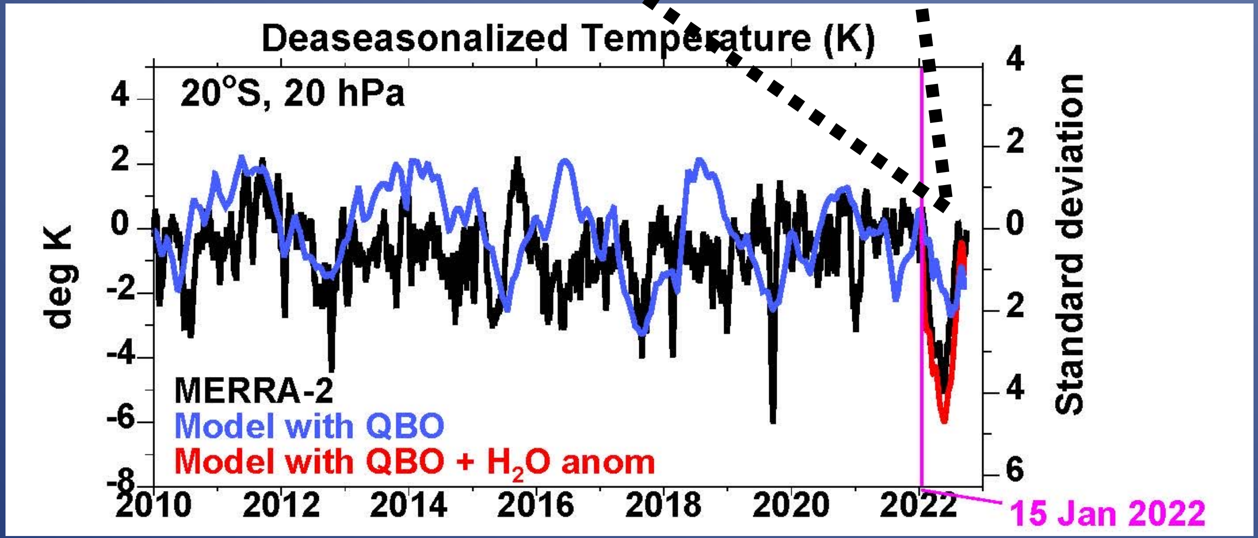

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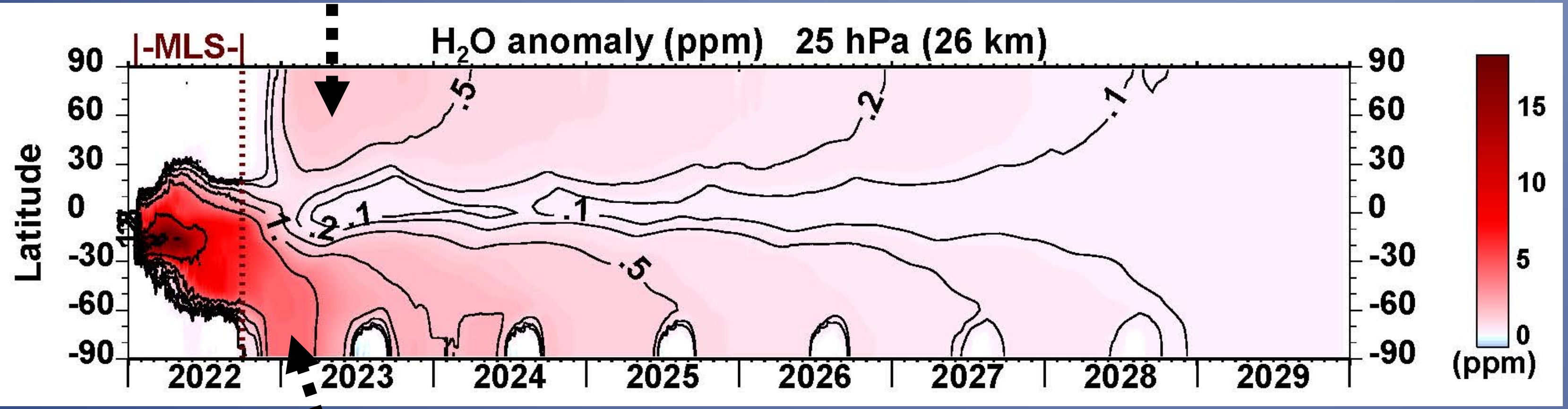
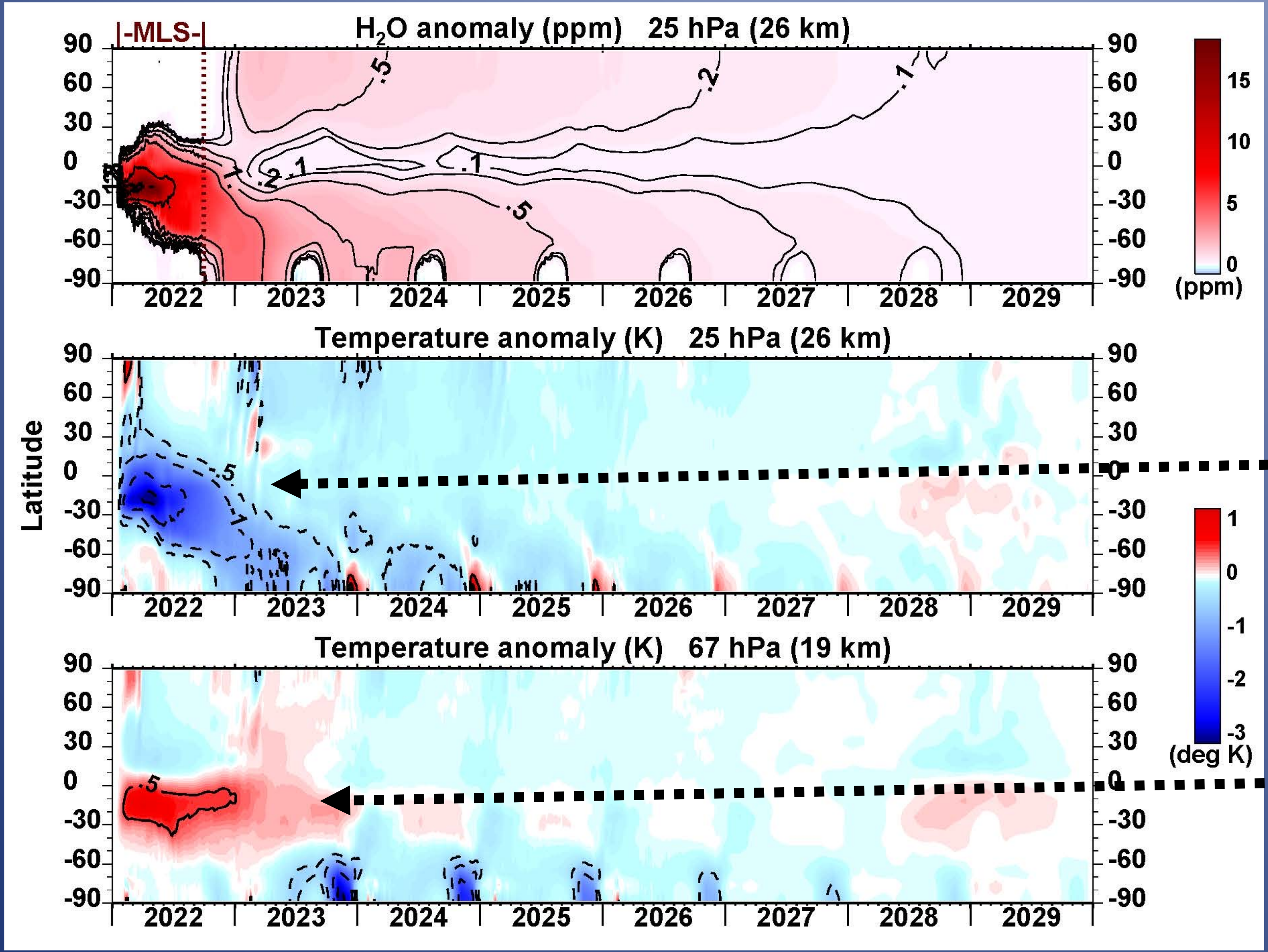
Long term response (2022-2029)

H_2O transported to NH in 2023 (~ .5 ppm)



H_2O anomaly transported to SH Pole in late 2022-2023 (2-3 ppm)

Long term response (2022-2029)

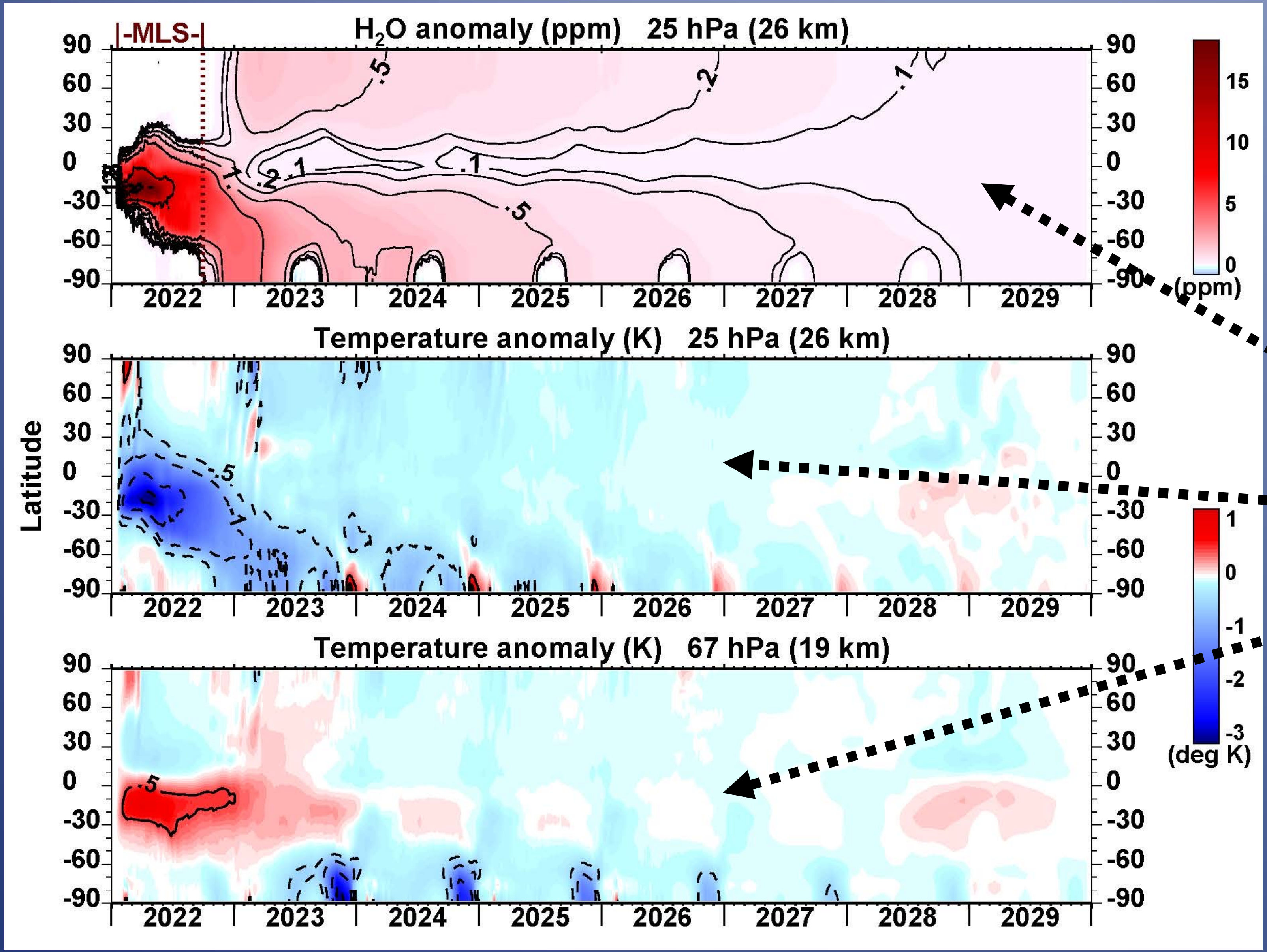


Largest temperature anomalies in tropics and SH 2022-2023:

Mid-stratospheric cooling of -.5 → -3K

lower-stratospheric warming of .2 → 1K

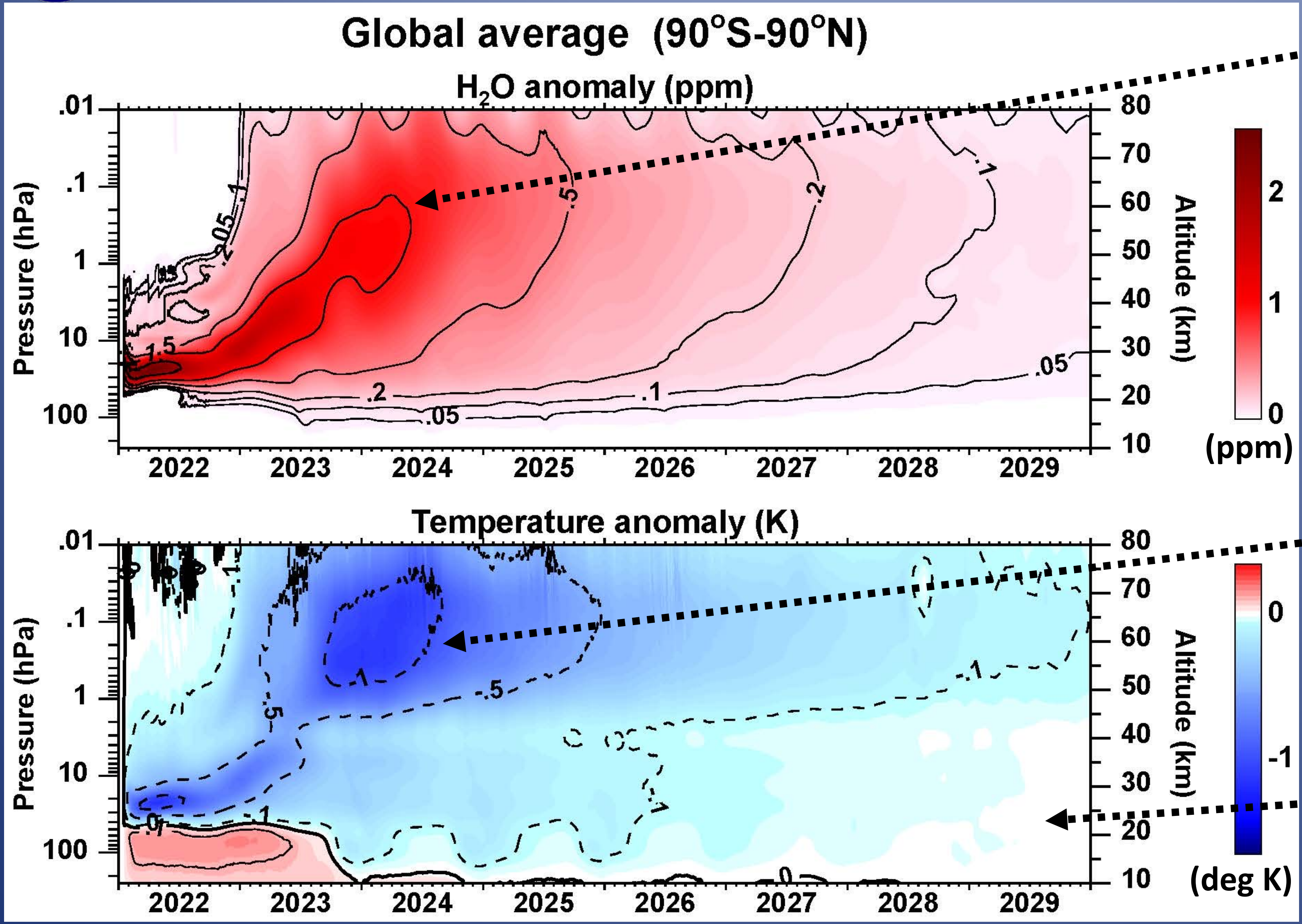
Long term response (2022-2029)



H_2O reduces to <.1 ppm globally by 2029

Mostly small cooling (-.1 → -.2K) throughout strat after 2024

Long term response (2022-2029)



H_2O anomaly transported to mesosphere

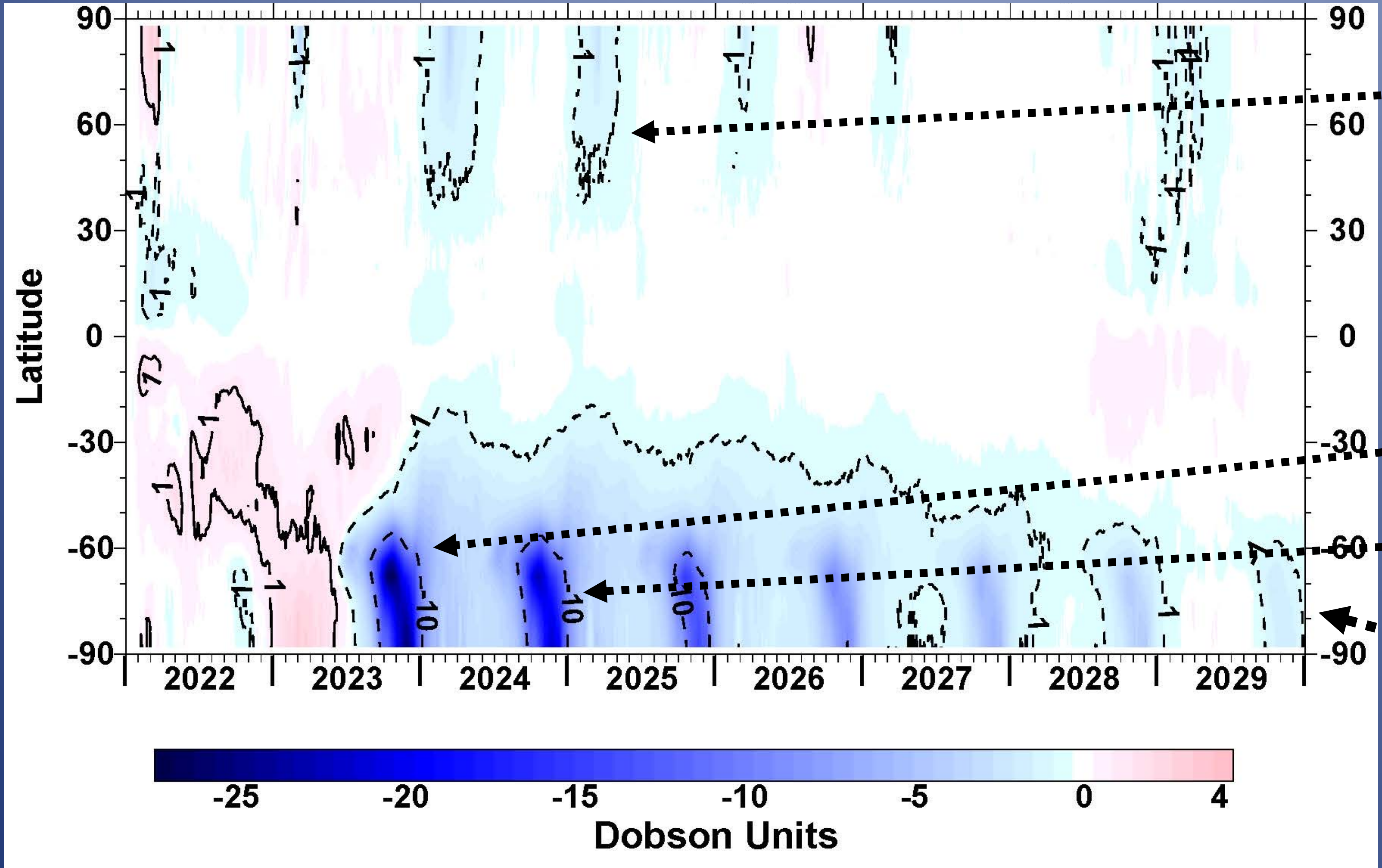
.5-1 ppm globally by 2023-2024

reduces to < 0.1 ppm by 2029

Mesospheric cooling of -1 → -1.5 K in 2023-2024 - 0.1 K by 2029

near-zero global stratospheric temp response by 2029

Total ozone response (2022-2029)



Small changes in NH
-1 → -2 DU in 2023-2025

Ozone hole:

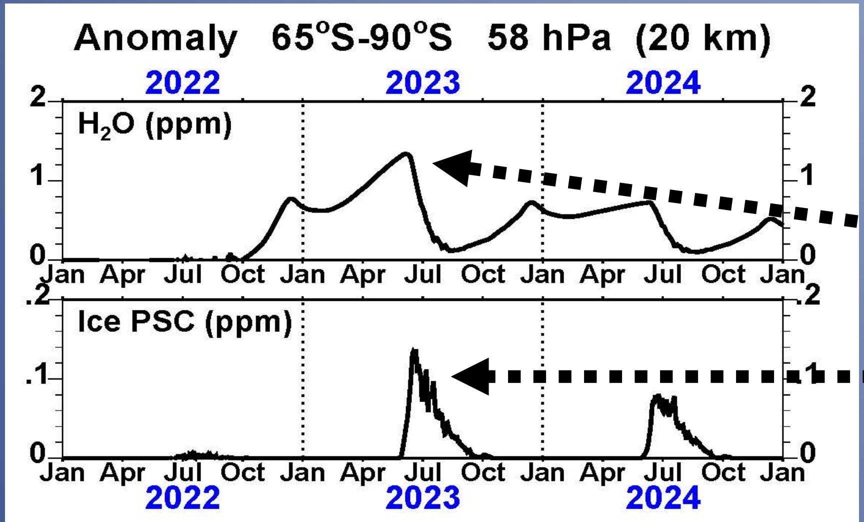
Small change in 2022

20-25 DU deeper in 2023

15-20 DU deeper in 2024

1-2 DU deeper by 2029

Ozone hole response (2022-2024)

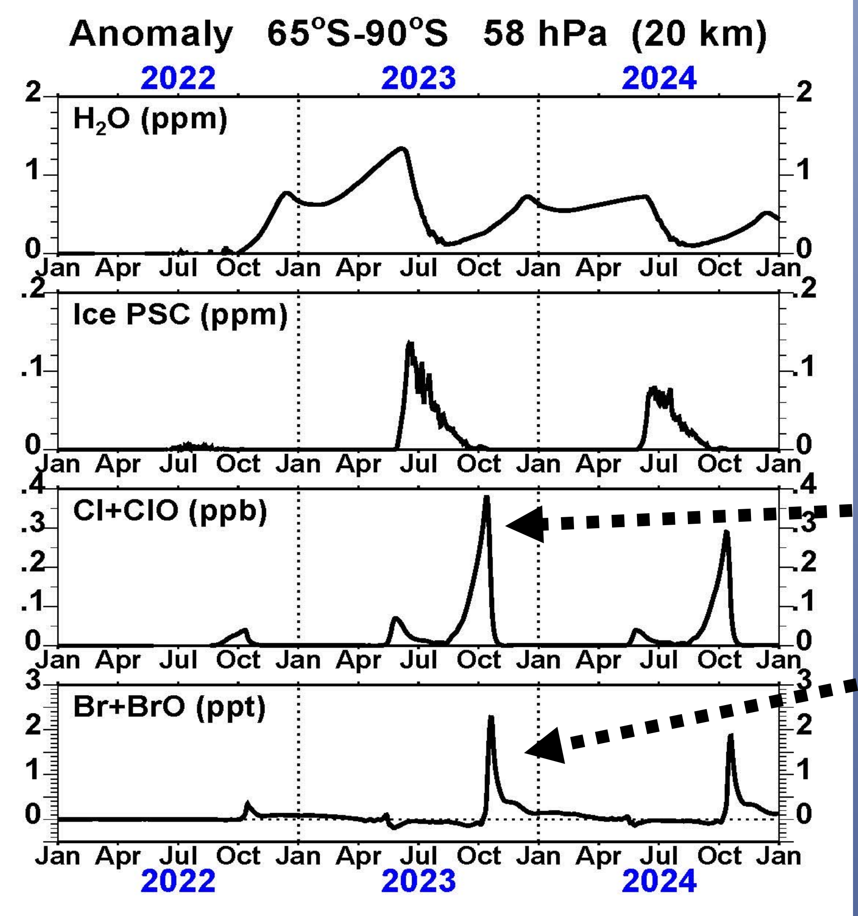


Very small impact until late 2022

significant H_2O increase in 2023 (~+1 ppm)

increase in ice PSCs ; (early winter increase in NAT PSCs)

Ozone hole response (2022-2024)



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PSC het reactions convert HCl and $ClONO_2$ → Cl, ClO

also convert bromine → Br, BrO

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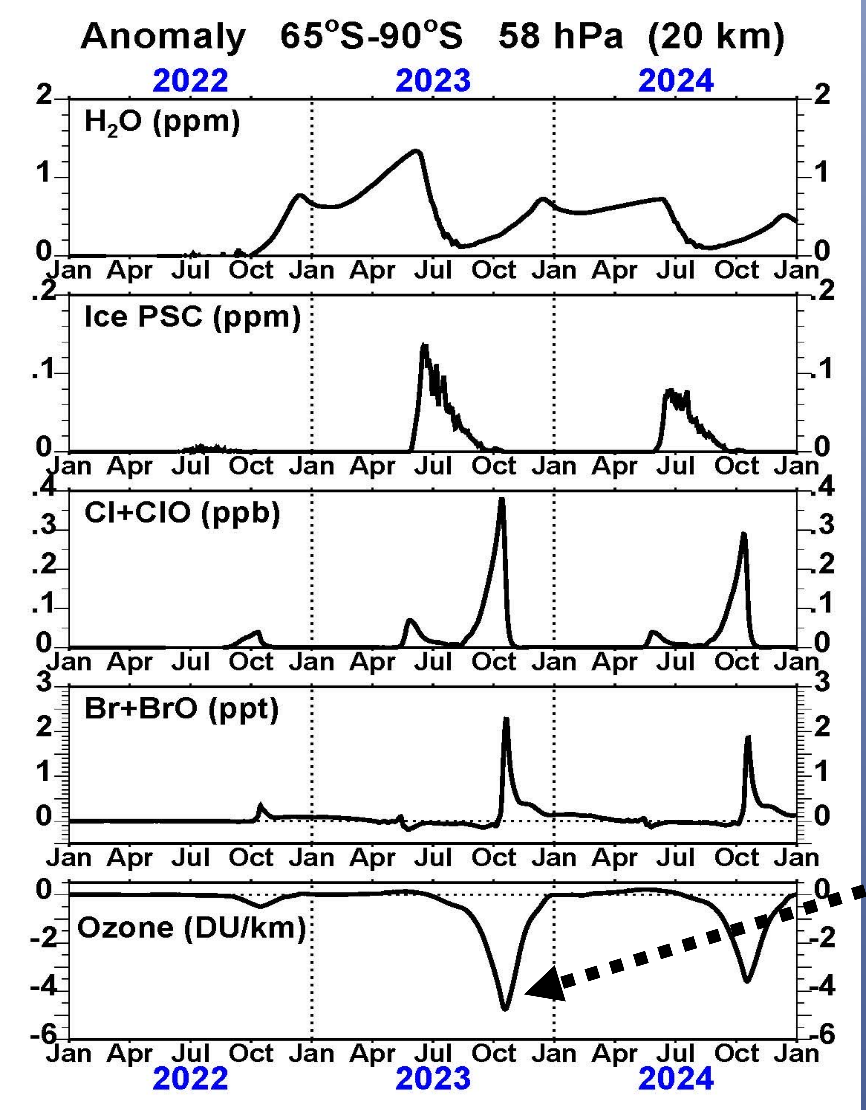

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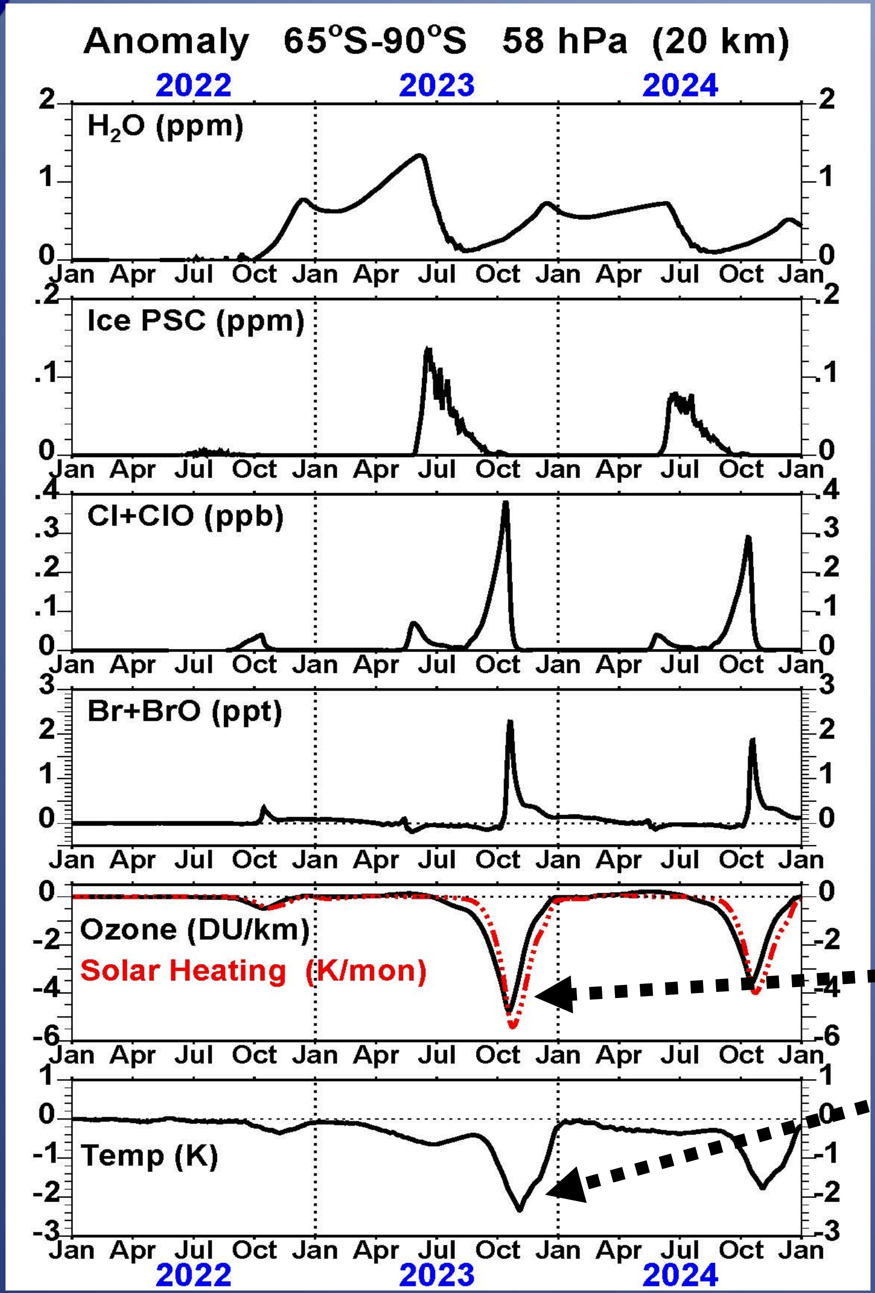

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significant ozone loss in spring → reduced ozone heating

significant springtime cooling (-2 → -3 K in November)

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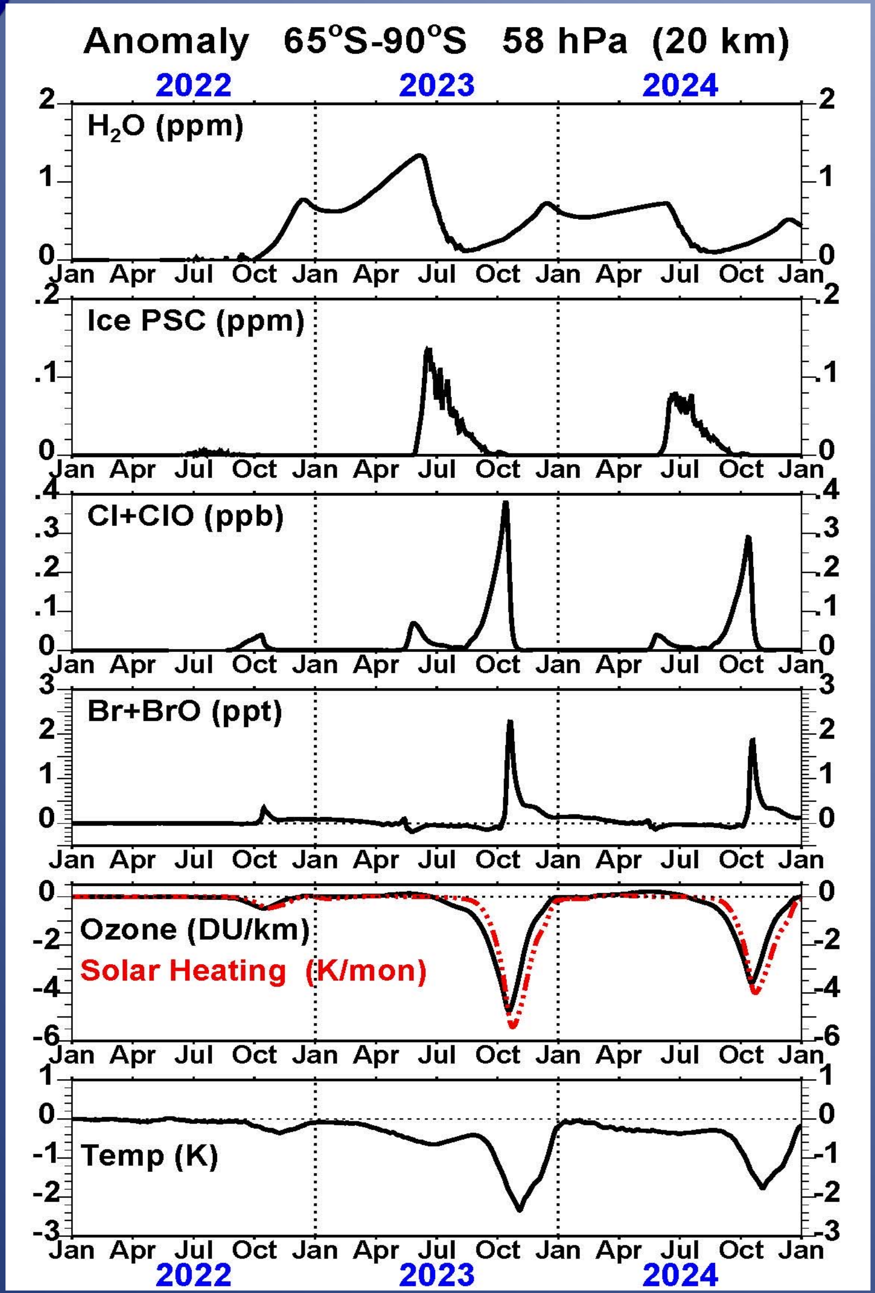

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anomalies are reduced in 2024 and each year thereafter

Summary

Hunga Tonga-Hunga Ha’apai water vapor impact:

- maximum model temperature anomalies in March-June 2022
- 2-3K cooling in SH mid-stratosphere ; ~1K warming in lower stratosphere
- combined with model QBO circulation explains much of the near-record MERRA-2 cold anomaly in SH subtropical mid-strat in May 2022
- water vapor transported to mesosphere → 1-1.5K cooling in 2023-2024

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- combined with model QBO circulation explains much of the near-record MERRA-2 cold anomaly in SH subtropical mid-strat in May 2022
- water vapor transported to mesosphere by 2023-2024 → 1-1.5K cooling

- Model ozone hole 20-25 DU deeper in 2023 ; 15-20 DU deeper in 2024

  increased ice (type II) PSCs in Antarctic starting 2023

  → increased conversion to active Cl, Br species → polar ozone loss

  small total ozone impact in NH (-1 → -2 DU)

  very small impact on total ozone and temperature globally by 2029